Blade Design with Engineered Cores Materials

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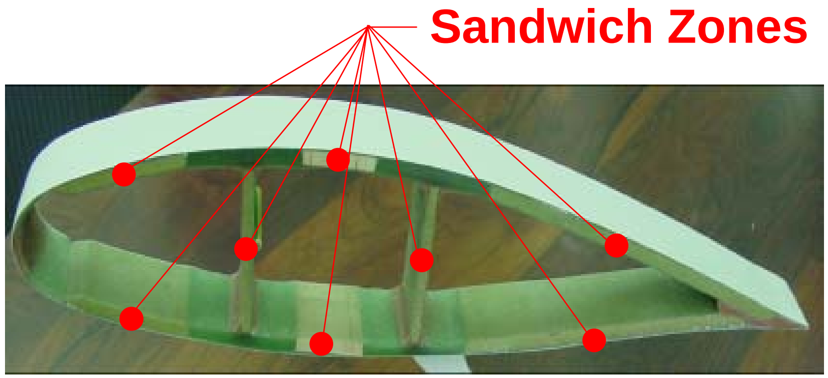
Sandwich Construction in Large Blades



<u>Characteristic Section of Large Wind Turbine Blade</u>

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- **As blade sizes have grow, sandwich construction has become prevalent**
- **Core Selection:**
  - **Affects weight, cost, and structural performance**
  - **Core optimization is a natural part of blade design optimization**

TOPICS

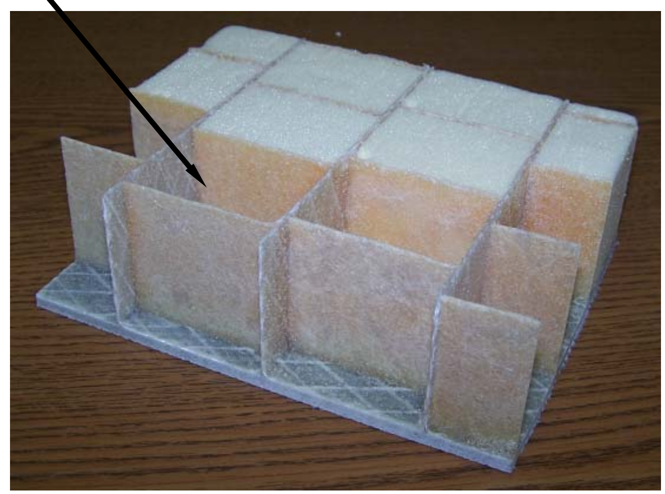
- Introduction to TYCOR® Engineered Core Materials
- Core Performance Issues in Blades
- Experimental and Analytical Comparison of TYCOR, PVC foam and Balsa Core Materials
  - Design for Buckling Resistance
  - Local Strength Measurements of Sandwich Laminates
  - Weight and Cost

TYCOR® Fiber Reinforced Core (FRC)

- **FRC has Web-Core Construction**
  - **Glass-fiber composite webs**
  - **Low-density (30 kg/m^3) polyisocyanurate foam**
- **Unidirectional or Bi-directional Web Orientation**
- **High specific stiffness and strength**

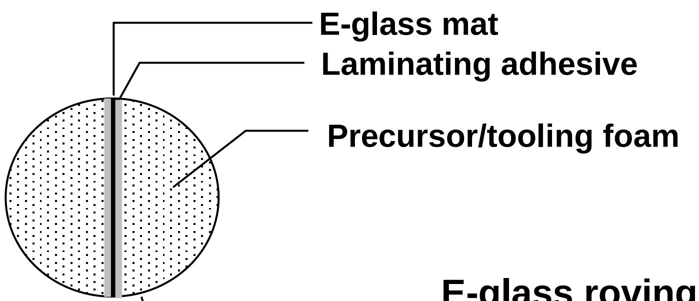
Foam removed to display webs

<u>Sandwich Panel with Unidirectional FRC</u>

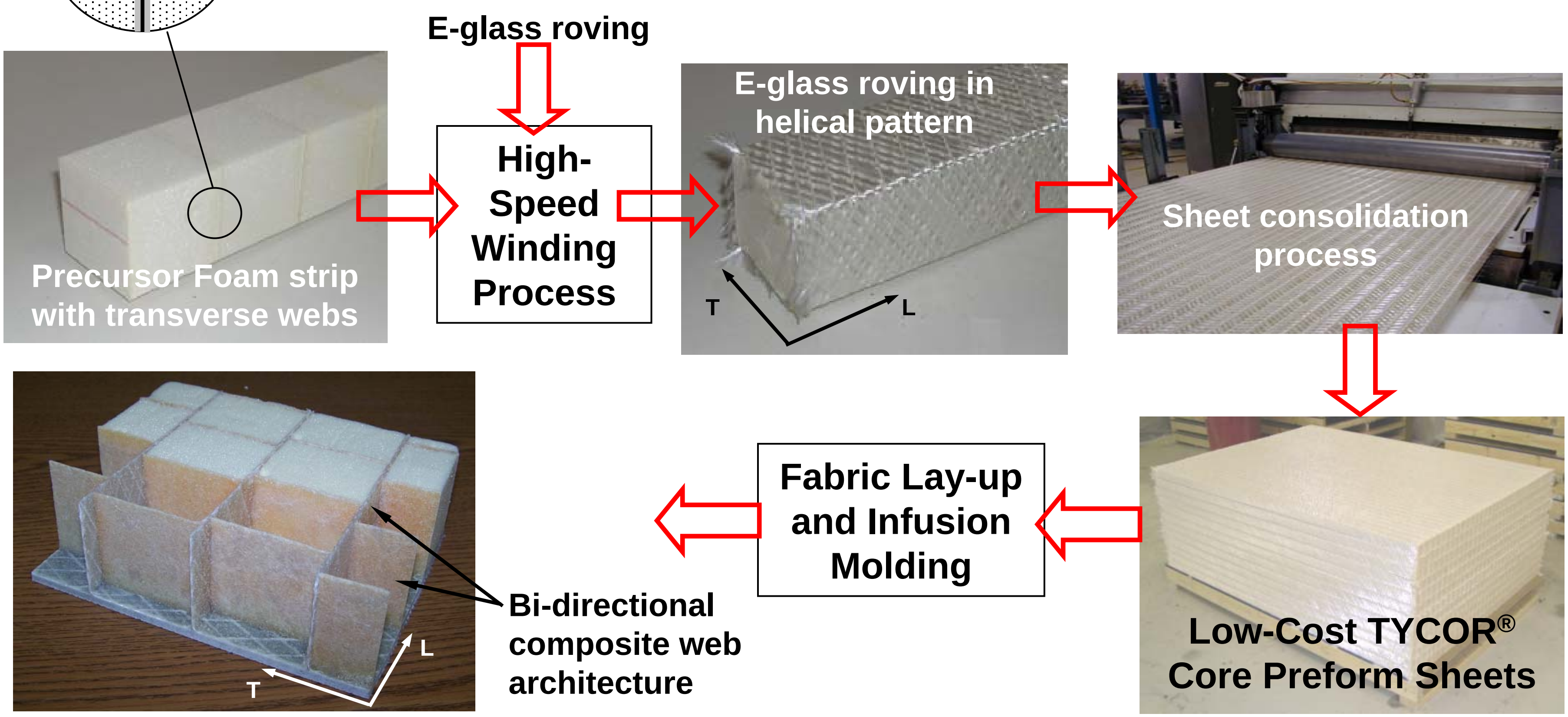


<u>Sandwich Panel Interior with “GX”-style Bi-Directional FRC</u>

"GX"-Style FRC for Infusion Molded Sandwich Structures



- **"Engineered Core:" Orthotropic stiffness and strength properties can be tailored independently in *L* and *T* directions**



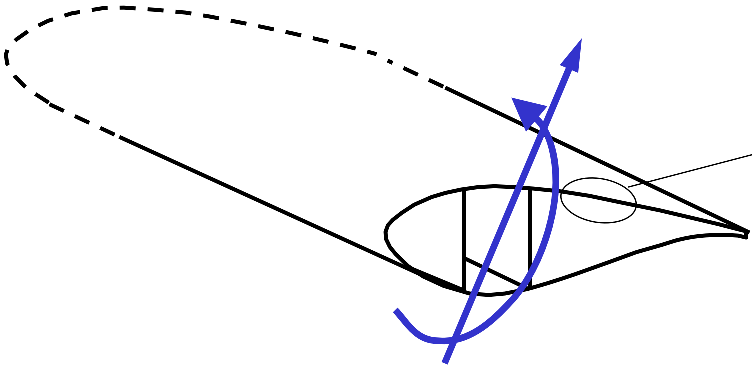
FRC Processing

- **<u>Conformability:</u>** **Conforms to characteristic blade skin curvatures**
- **<u>Machining:</u>** **Dry preform cuts easily with band saw, table saw, utility knife, etc.**
- **<u>Infusion Molding:</u>** **Works well in vacuum infusion with single-side feed due to through-thickness porosity**
- **<u>Sheet Size:</u>** **Large sheet size minimizes handling (e.g. 1.2m $\times$ 2.4m or larger)**

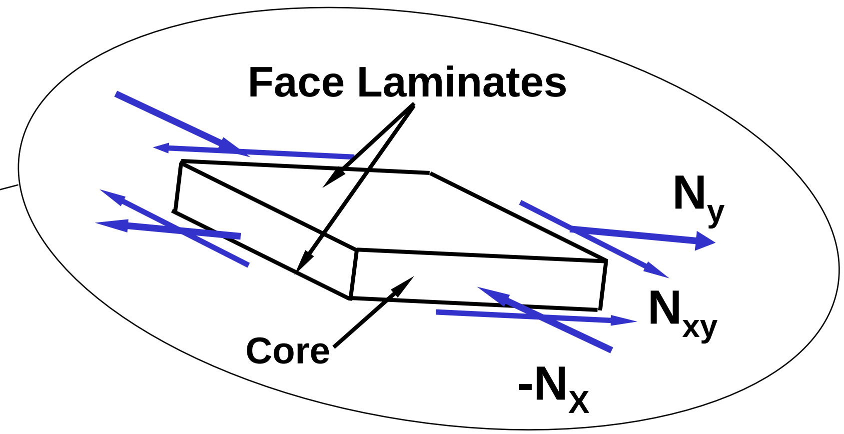
Status of FRC in Blades

- WebCore supported Global Energy Concepts and TPI Composites in DOE SBIR Project, fabricating two MW-scale research wind turbine blades featuring TYCOR core.
  - All TYCOR kitting was performed on-site with simple shop tools (table saw, utility knives).
  - All eight lay-ups and molding-infusions went smoothly.
- FRC is nearing certification for use in shear webs, replacing balsa for a 2+MW turbine system
- Completed initial feasibility study of FRC as complete-blade PVC foam replacement for second wind turbine manufacturer. Showed significant cost and weight reductions.

Characteristic Sandwich Loading



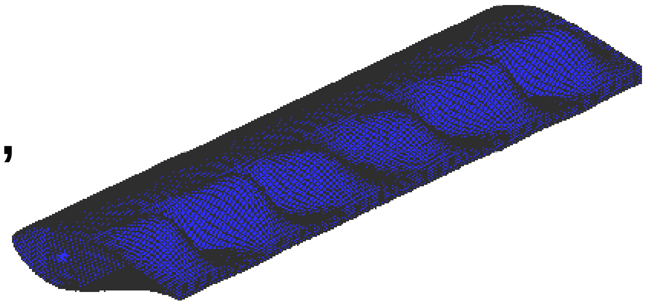
Net Loads on Blade Section



Local Sandwich Loads

- **Local Sandwich Loading - predominantly in-plane**
- **Face Laminates - designed to provide strength and stiffness for global blade response**
- **Sandwich Construction - serves to increase local bending stiffness of laminates to control local bending and suppress buckling**
- **Core Loading - minimal direct loading traditional sense (Transverse shear, through-thickness compression/tension)**

Core-Related Structural Performance Considerations



- **Global or Panel-Level Buckling**
  - **Core affects buckling design margins, must meet minimum requirements**
  - **Assessed analytically**

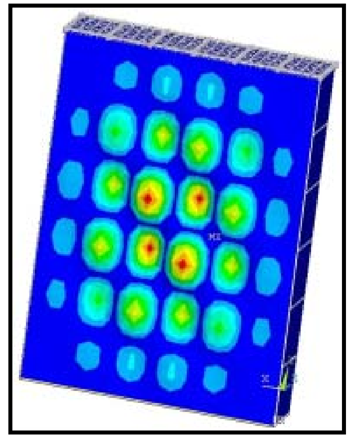
- **Local Sandwich Laminate Strength (In-Plane)**
  - **"Don't mess things up" - Core must enable face laminates to achieve required static and fatigue strength**
- **Sandwich Transitions**
  - **Laminate strength at core thickness transitions**
  - **Laminate strength at core closeouts**

In-Plane Strength Example: Local Failure Modes for Edgewise Compression

Method: **ASTM C 364/C 364M – 06 "Standard Test Method for Edgewise Compression Strength of Sandwich Constructions"**

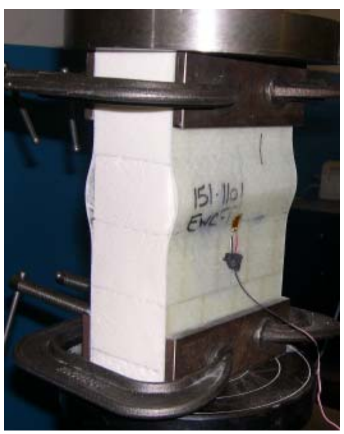
Test configuration

Face compression failure



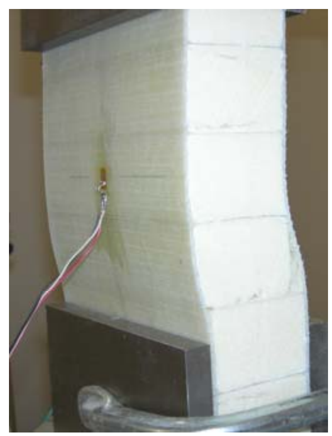
Face buckling between webs

Local buckling of face



Face buckling/ debond from core

Face buckling/ debond from core



Core shear instability (global mode)

Edge crushing (invalid mode)

Study: Experimental and Analytical Comparison of FRC, PVC foam and Balsa Core Materials

Alternate core materials:

- **Low-density PVC foam (60 kg/m^3)**
- **Medium-density end-grain balsa**

Compare:

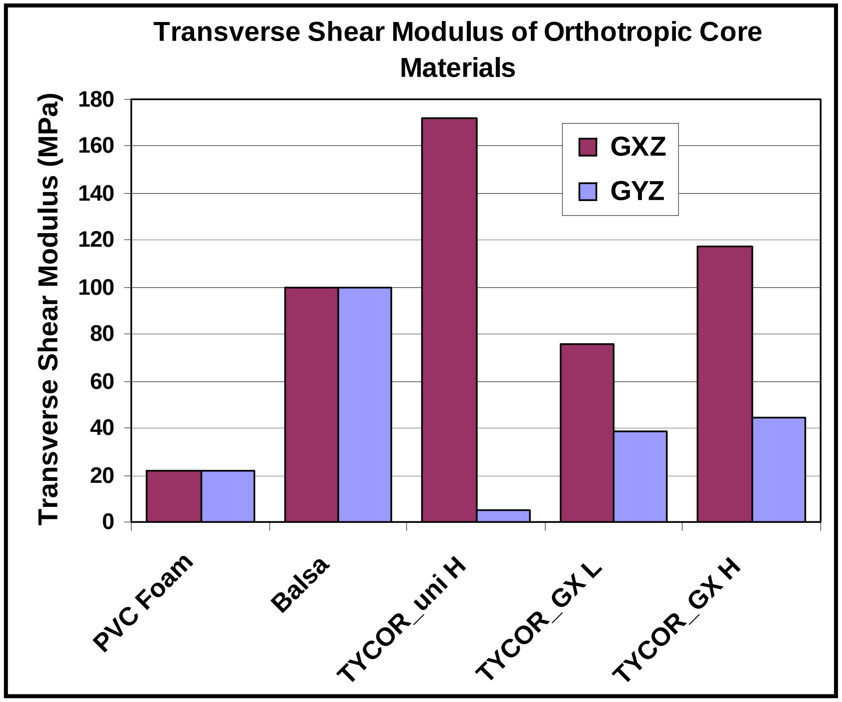
1. **Blade buckling resistance**
2. **Local strength of sandwich laminates under in-plane loading**
3. **Core weight and cost**

Blade Buckling Analysis

- **Core Material Properties**
  - A general core material is orthotropic
  - Transverse shear modulii have large effect on global buckling

Descriptions of Cores Used in Study

Core	Description
Low-density PVC Foam	Airex C70.55, 60 kg/m^3 density
Medium-density Balsa	ProBalsa® Standard, 155 kg/m^3 density, "Minimum" properties
TYCOR_uni H	High-strength uni-directional FRC
TYCOR_GX L	Lower-property GX FRC
TYCOR_GX H	Higher-property GX FRC



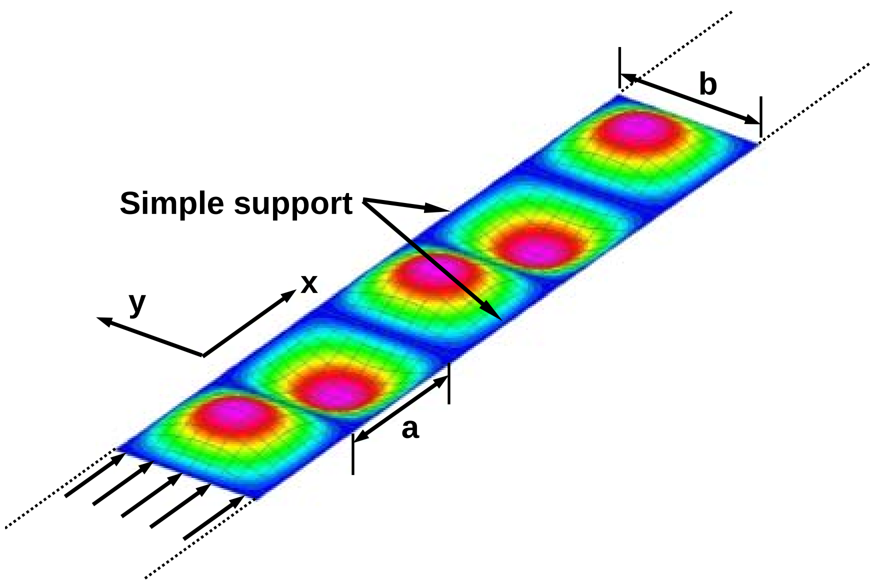
Orthotropic Elastic Input Parameters for FEA

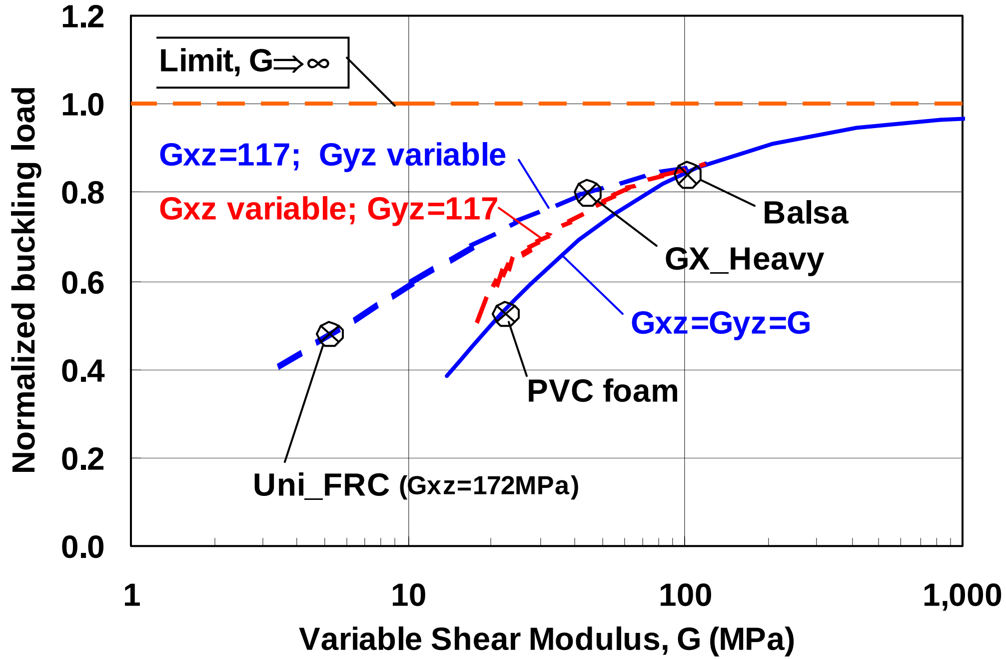
	Extens. Stiffness (Gpa)			Shear Stiffness (Gpa)			Poisson's Ratio		
Material	E_X	E_Y	E_Z	G_{XY}	G_{YZ}	G_{XZ}	NU_{XY}	NU_{YZ}	NU_{XZ}
E-TLX_3300	18.28	11.25	11.25	6.26	3.74	3.74	0.494	0.213	0.270
PVC Foam	0.045	0.045	0.069	0.022	0.022	0.022	0.200	0.200	0.200
Balsa	0.400	0.400	2.000	0.025	0.100	0.100	0.200	0.200	0.200
TYCOR_uni H	0.248	0.016	0.248	0.0018	0.0052	0.1720	0.377	0.025	0.500
TYCOR_GX L	0.145	0.069	0.269	0.0018	0.0386	0.0760	0.029	0.116	0.267
TYCOR_GX H	0.207	0.076	0.345	0.0018	0.0441	0.1170	0.002	0.102	0.310

Flat-Plate Buckling Analysis

Uniaxial Compression of Plate Strip

- <u>Goal:</u> **Simulate a strip of *blade skin*, explore effects of orthotropic core transverse shear modulii, G_{XZ}, G_{YZ}**
- <u>Analysis method:</u> **Double-Fourier series solution for thin-faced sandwich**
- <u>Laminate:</u> **Core thickness=37mm, Face thickness=2.6mm of E-TLX 3300 ([0/±45]), Width b=100 mm**





⇒ ***As G decreases, buckling load decreases***

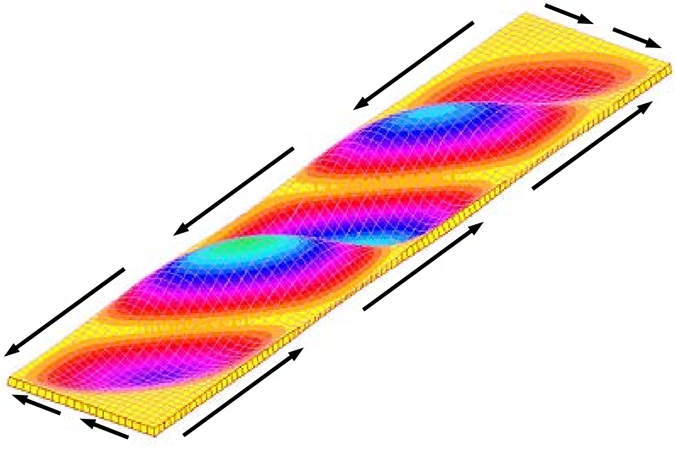
⇒ ***FRC and balsa can be used at lower thicknesses than low density foams***

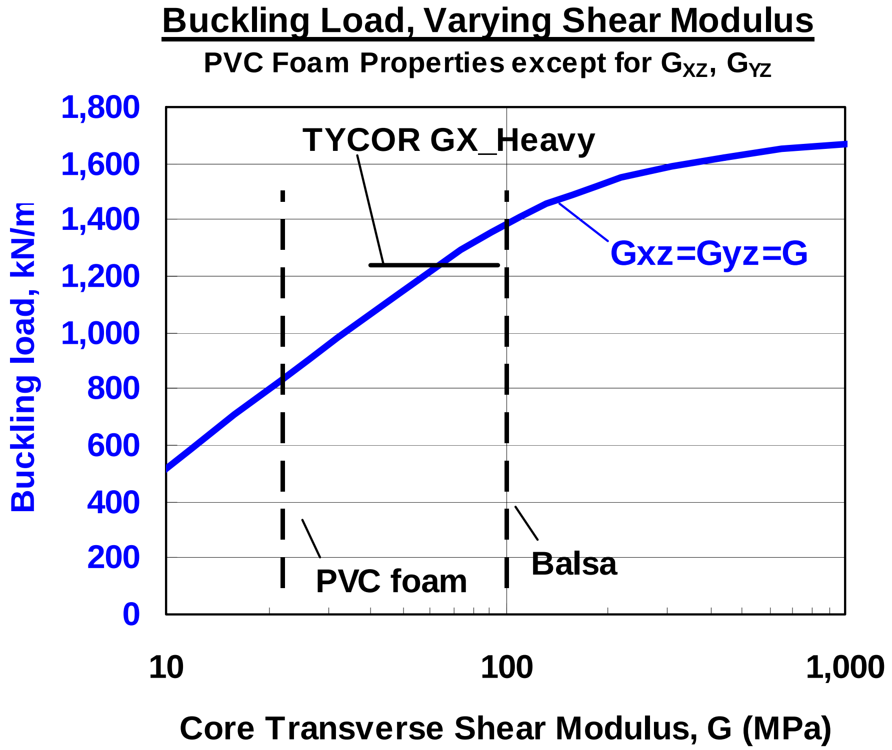
⇒ ***For Orthotropic core, Gxz (compression axis) should be greater than Gyz***

⇒ ***Gyz can be reduced somewhat lower than Gxz (for weight and cost reduction) with only small loss in buckling performance***

Flat-Plate Buckling Analysis
In-Plane Shear of Shear-Web Laminate

- **Simulate a Shear-Web laminate under in-plane shear using FEA**
- **Rectangular panel, simple edge support, 1m wide by 5m long**
- **Demonstrate sensitivity of buckling to transverse shear modulus of core, G**
- **Core thickness=50mm, Face thickness=1.5mm, +-45° E-glass reinforcement**

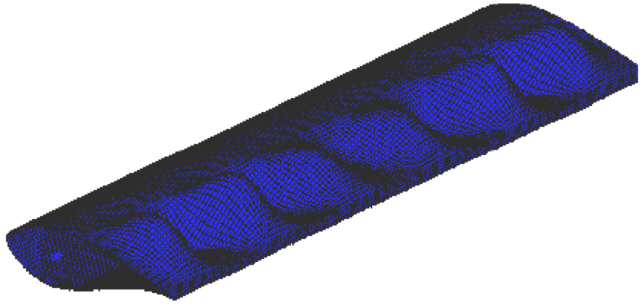




⇒ ***Buckling resistance decreases as G decreases***

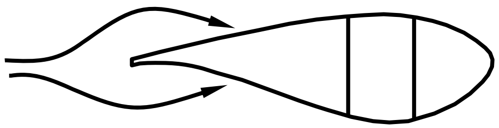
Blade Buckling Analysis

- Blade shape and design loads from conceptual design study conducted by GEC under U.S. DOE-sponsored WindPACT program
  - Fiberglass blade, 43.5m long
  - 2.5MW turbine



Buckling in Constant-Section Model

- NuMAD (Sandia Nat'l Lab) preprocessor with ANSYS FEA code.
- Targeted buckling studies at 25%, 50%, 75% (not completed) span stations
- Focused on aft-skin buckling performance



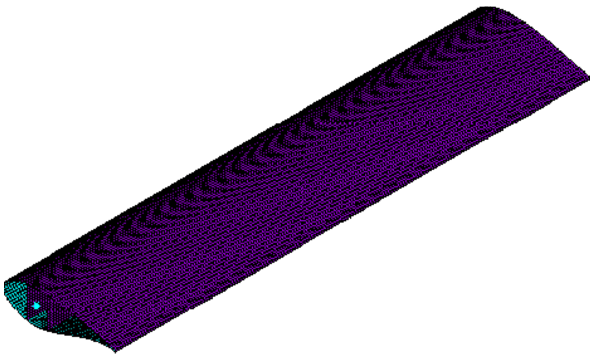
Key Span Stations and Loads

r/R	r (m)	Airfoil	Chord (m)	Design Loads (kN-m)	
				Flap	Edge*
0.025	1.125	Cylinder	2.25	6,763.5	3,172.5
0.250	11.250	DU97-W-300	3.60	3,982.5	1,552.5
0.500	22.500	DU91-W2-250	2.60	1,890.0	545.3
0.750	33.750	DU93-W-210	1.60	448.1	96.2

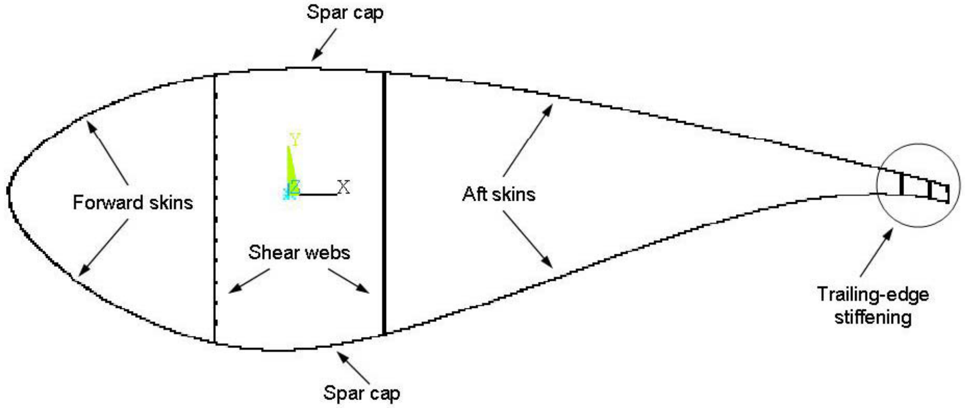
* Peak value of negative edge bending (trailing edge in compression)

Blade Buckling Study

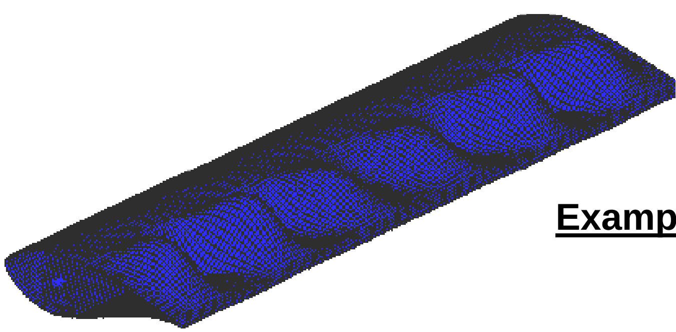
- **Approach**
  - **Apply design load (moment) to constant-cross-section model of corresponding blade station**
  - **Vary core thickness in the <u>aft skins</u> to determine minimum core thickness that satisfies required buckling margin**



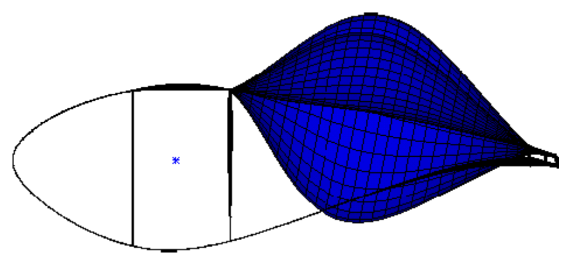
<u>Example constant-section model</u>



<u>Characteristic blade section</u>



<u>Example buckling mode</u>

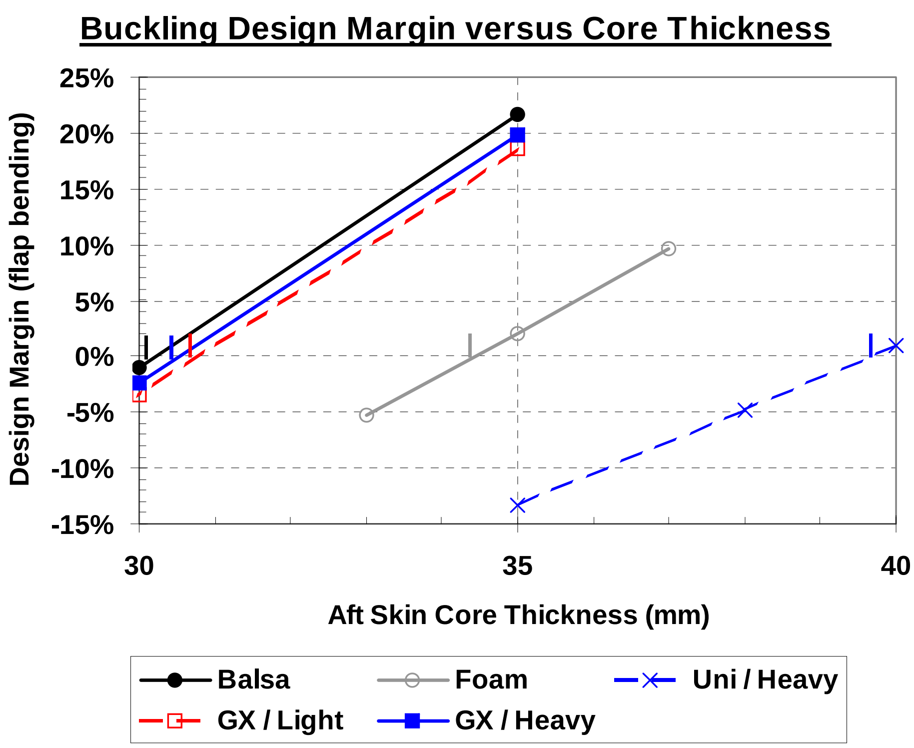


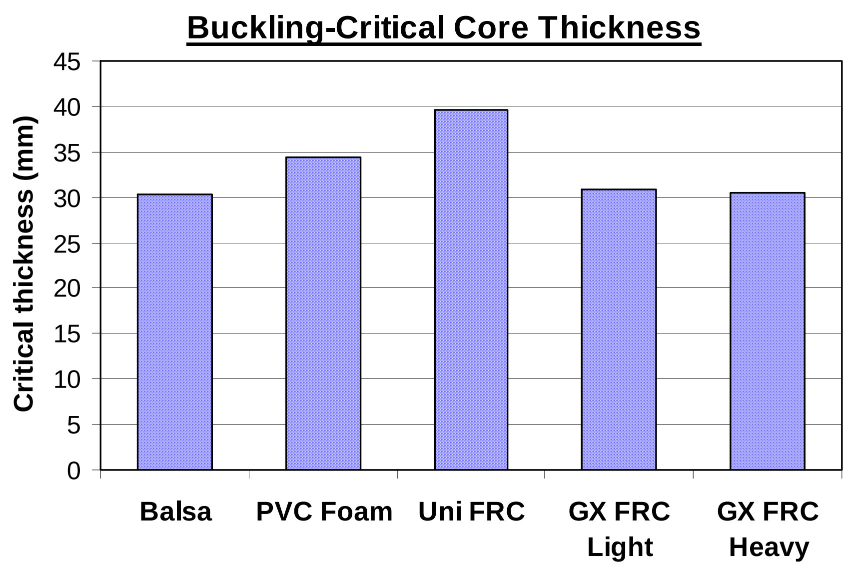
Blade Buckling Study - 25% Span Station Results

⇒ ***GX-FRC designs perform similarly to balsa***

⇒ ***GX-FRC enables 11% thickness reduction compared to PVC foam***

⇒ ***Uni-FRC requires higher thickness***





Buckling Study Comments

- For buckling-critical laminates, FRC and balsa can be used at reduced thickness compared to PVC foam
- Future FEA Blade Analysis:
  - Expand to additional span stations
  - Expand to additional core areas (shear webs, forward skins)
- Challenges:
  - Finite element modeling approaches to account for transverse shear effects
  - Numerical problems in some design regimes (questionable local buckling modes)

Experimental Core Comparisons - Structural Performance, Weight, Cost

- **Two laminate styles:**
  - **Shear Web:**
    - 50 mm rigid cores (GXW1, balsa, PVC foam)
    - 2-ply and 3-ply faces, Double bias E-glass fabric [45/-45/mat], 0.69 mm/ply
    - Vinyl ester resin (in-plane shear) and Epoxy resin (edgewise compression)
  - **Blade Skins:**
    - 25mm contourable cores (GXW2, balsa, PVC foam)
    - 2-ply and 3-ply faces, Tri-axial E-glass fabric [0/±45], 0.51mm/ply
    - Epoxy resin
- **Total of 12 laminate designs molded and tested**
- **Comparisons**
  - **Local in-plane compressive and shear strength of laminates**
  - **Core weight and cost including absorbed resin**

Experimental Core Comparisons - Structural Performance, Weight, Cost

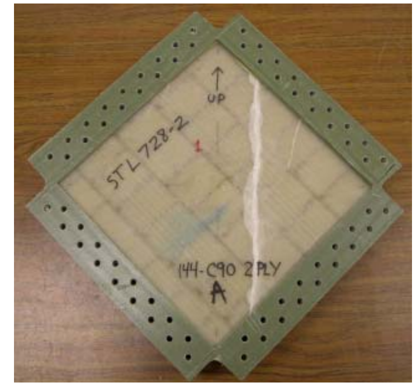
- **Five specific GX FRC designs investigated**

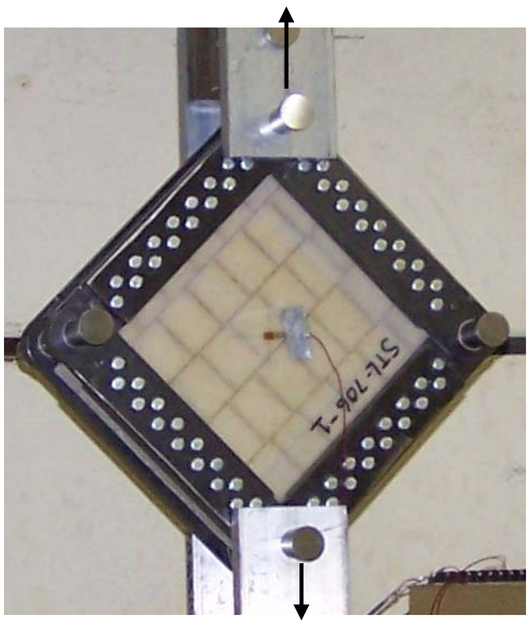
FRC Design ID	Background	L Webs			T Webs	
		Spacing (mm)	Fiber weight (gr/m^2)	Fiber angle	Spacing (mm)	Fiber weight (gr/m^2)
GXW1	For shear webs as balsa replacement	50	550	60º	38	300, random mat
GXW2	Modified GXW1 for reduced cost	50	550	45º	38	300, random mat
GXW4	Improved edgewise compression, Light	38	400	45º	38	300, random mat
GXW5	Improved edgewise compression, Heavy	38	550	60º	38	300, random mat
GX-Light	For shear webs as PVC-foam replacement	50	300	45º	38	2×75, foam-board facer

In-Plane Shear Strength of *Shear-Web Laminates*

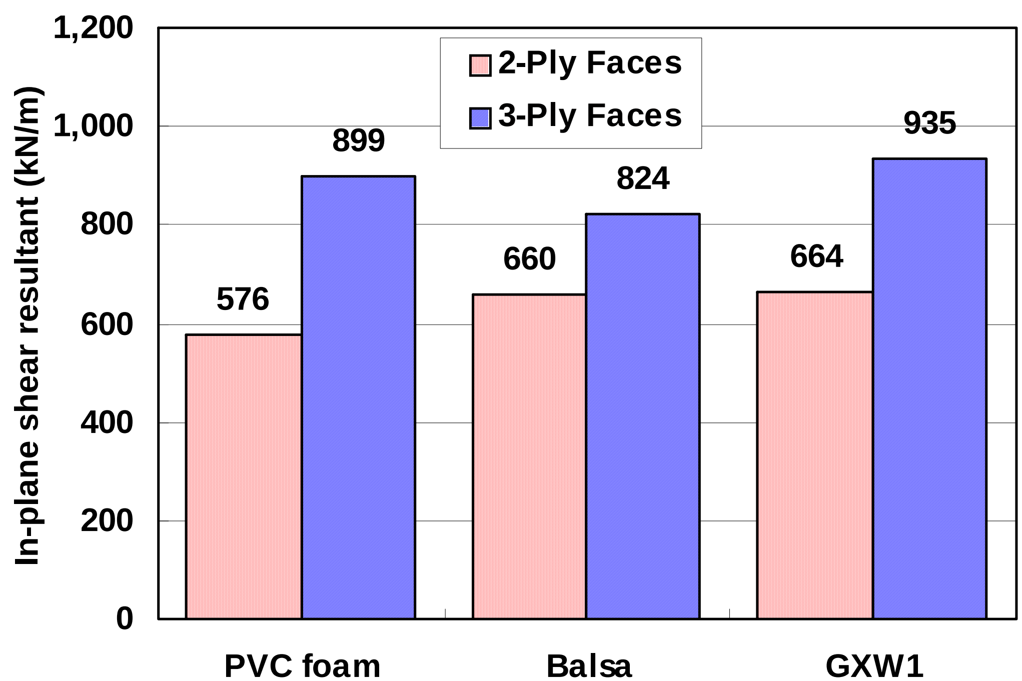
- **Primary loading for shear-web laminates**
- **Single-specimen values**

⇒ ***GXW1 FRC performed similarly to PVC foam and balsa***





Test Configuration
Bonded edge doublers
Specimen: 305 mm square
Open area: 230 mm square



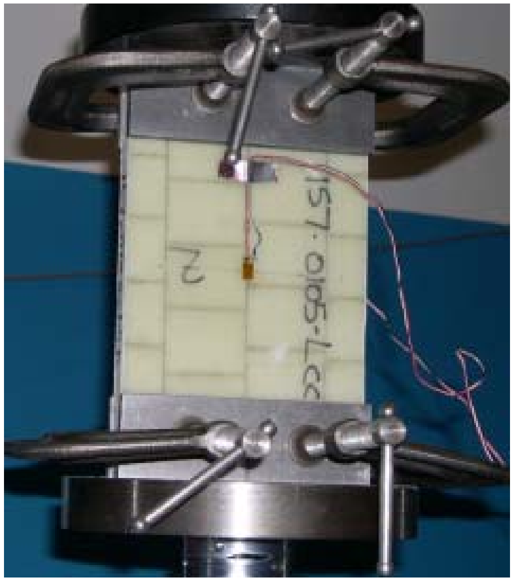
In-Plane Local Shear Strength

Edgewise Compression Strength of *Shear-Web Laminates*

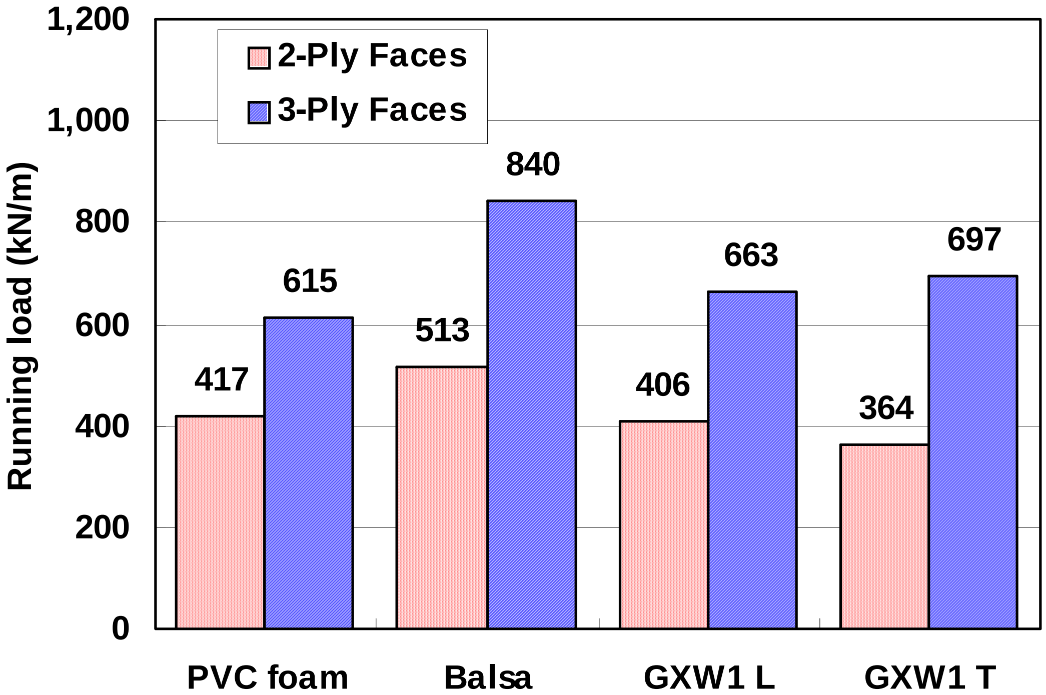
- **Important for compatibility of shear web with spar cap compression**

⇒ ***GXW1 performance comparable to PVC foam***

⇒ ***In practice: Design to strain requirement***



Test Configuration
Specimen: 250mm×150mm
Gage length: 150mm



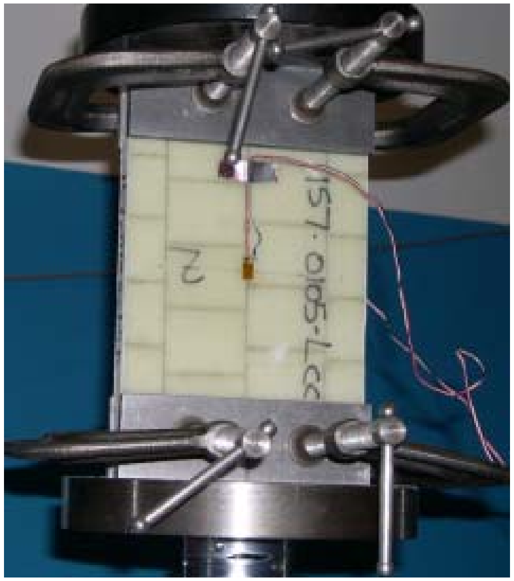
Local Edgewise Compressive Strength (3-Specimen Averages)

Edgewise Compression Strength of *Skin Laminates*

- **GXW2 performed lower than PVC foam and balsa**
- **GXW4 and GXW5 were designed to provide improve performance**

⇒ ***Demonstrates ability to engineer FRC to meet requirements***

⇒ ***In practice: Design to strain requirement***



Test Configuration
Specimen: 250mm×150mm
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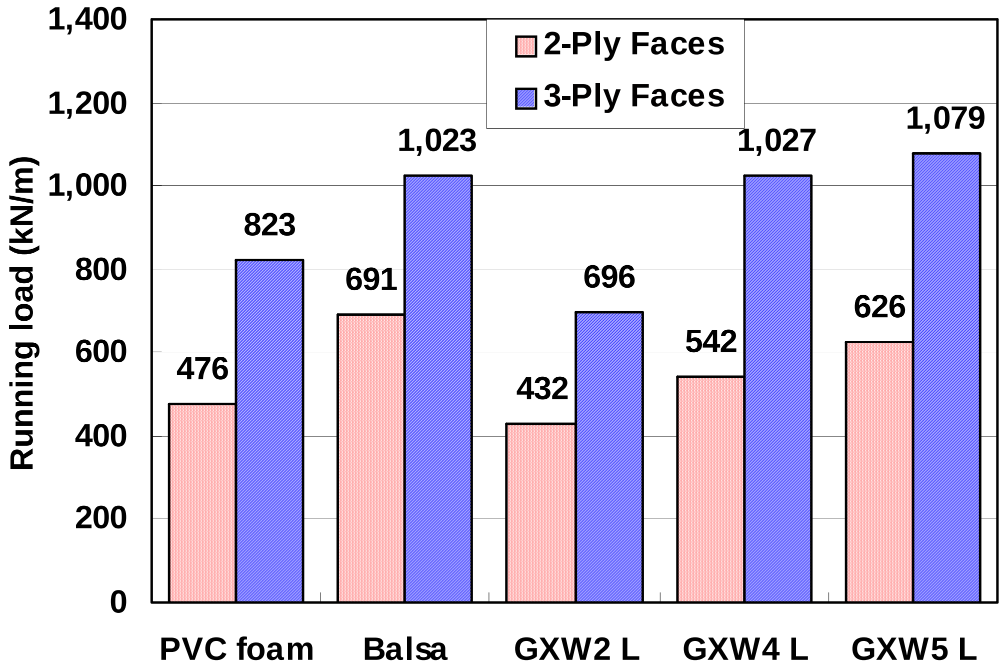
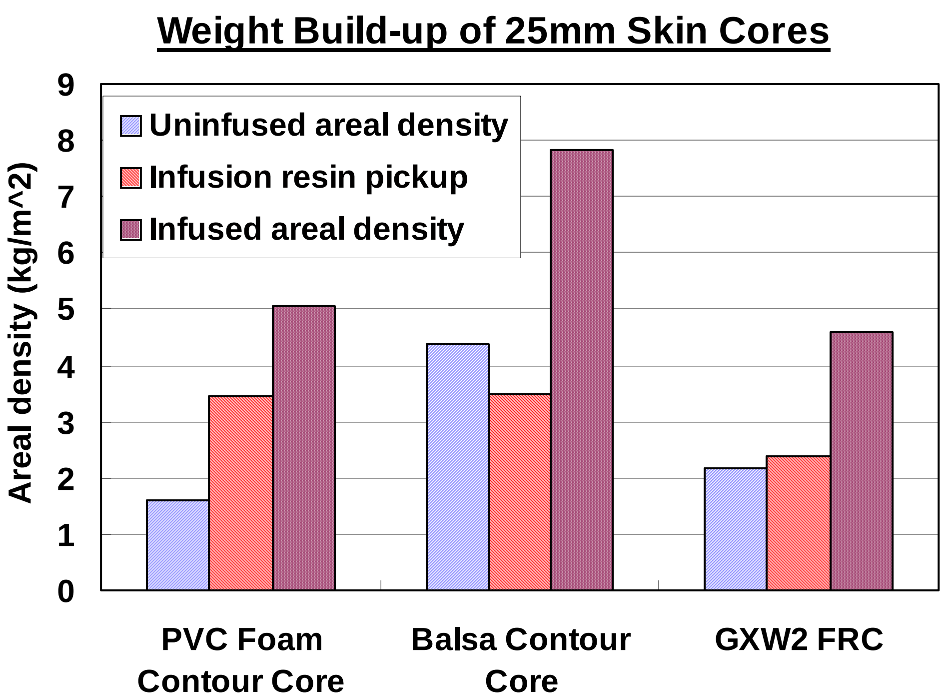


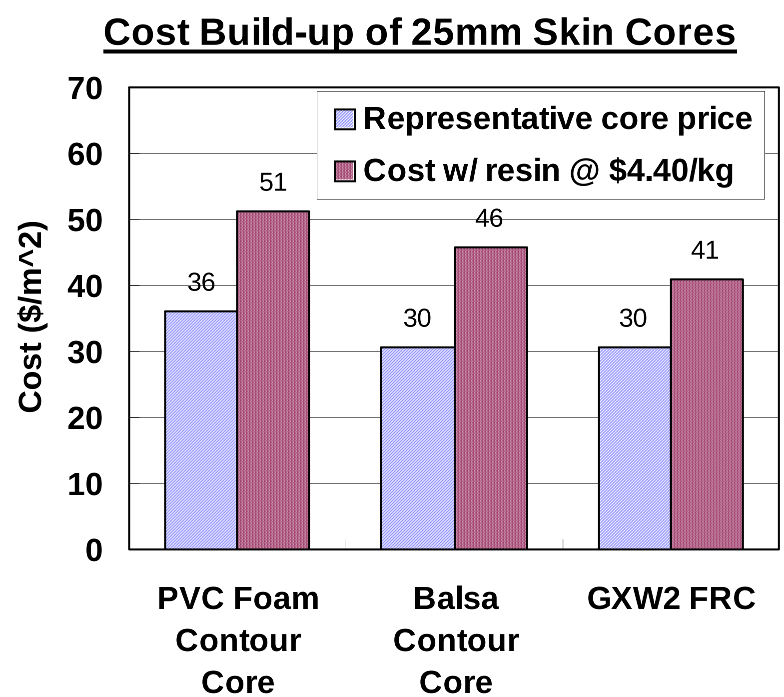
Local Edgewise Compressive Strength (3-Specimen Averages)

Weight and Cost Analysis

- **Note on Representative Core Prices**
  - **<u>PVC foam and balsa:</u> Representative prices, reflecting input from a variety of sources**
  - **<u>GX-FRC:</u> Price was set equal to balsa cost – This is a *conservative price* for high-volume applications**

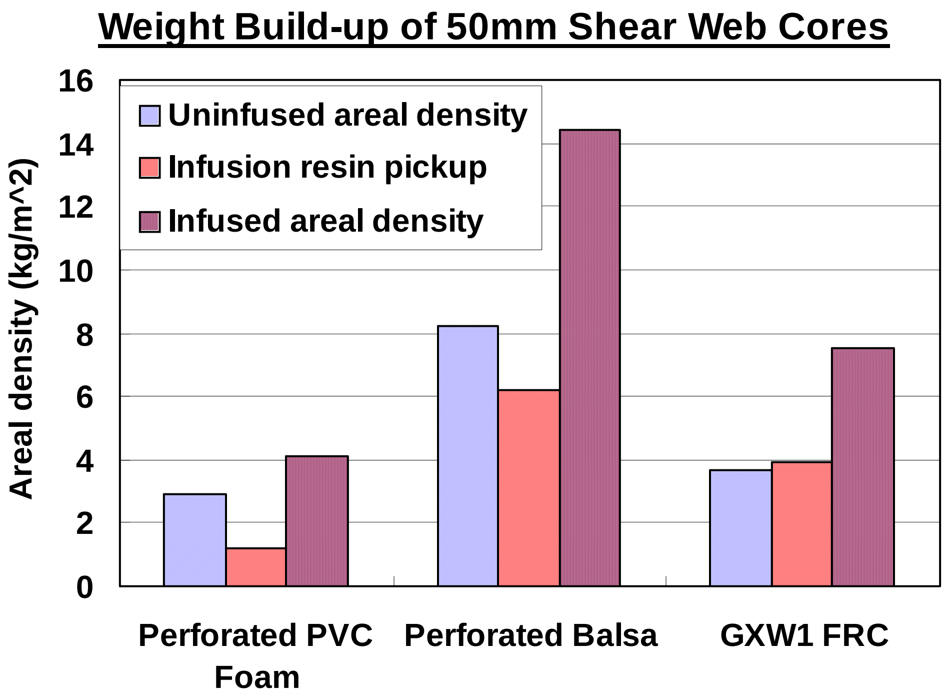
Weight and Cost–
25mm Blade Skin Cores

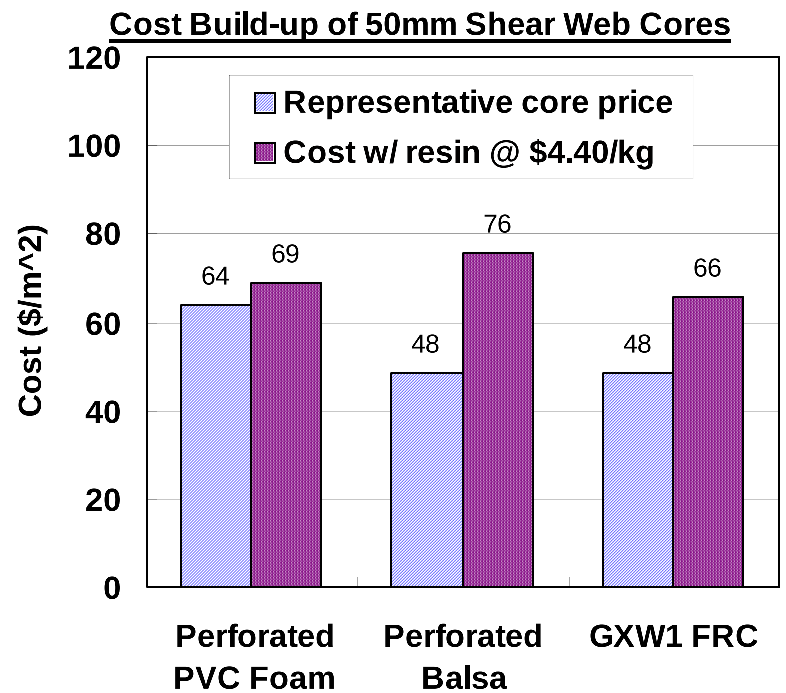




⇒ ***GXW2 FRC offers lower cost and weight than PVC foam and balsa at equal thickness***

Weight and Cost–
50mm Shear Web Cores

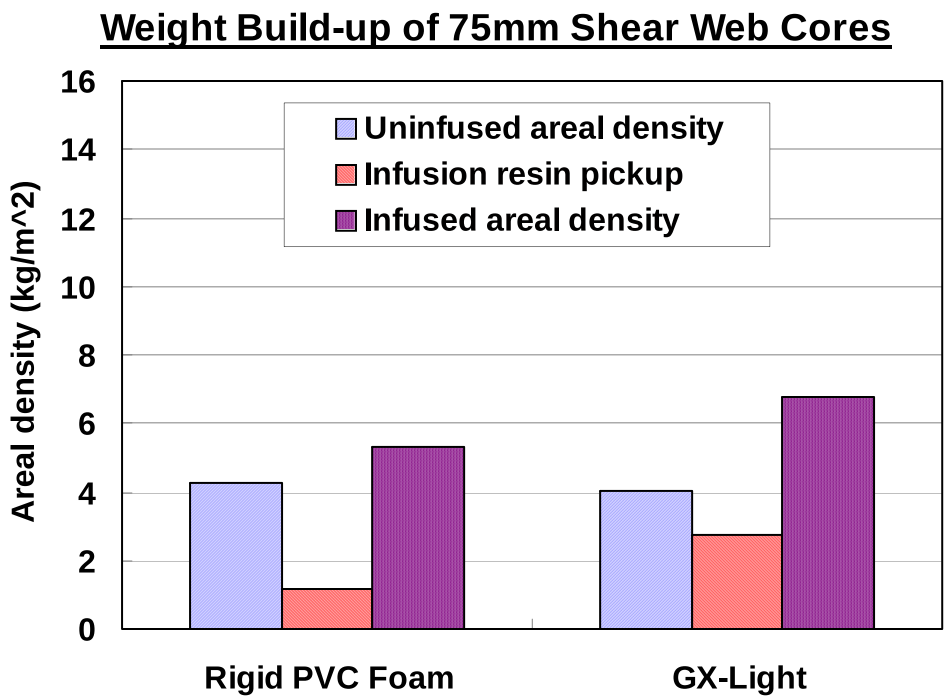


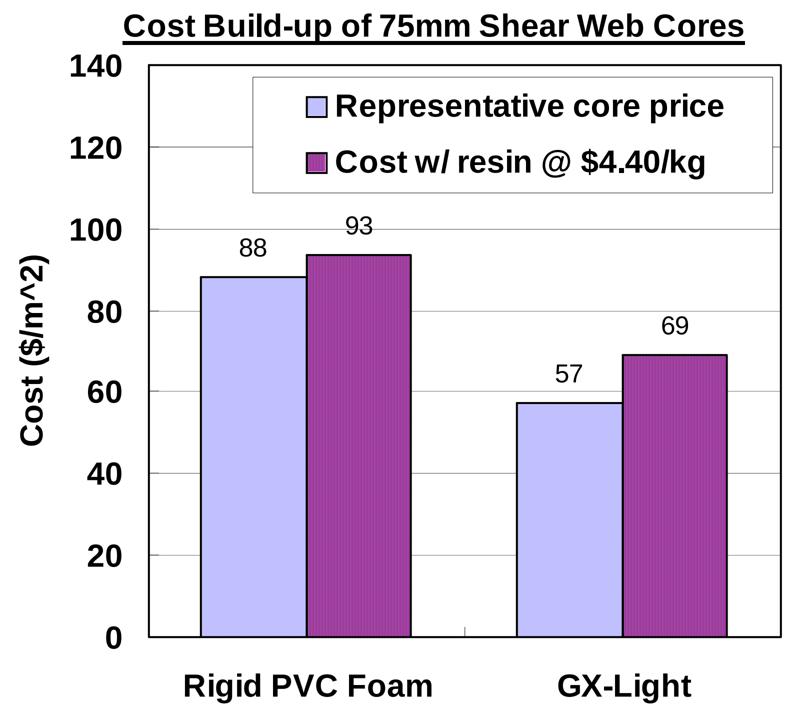


- ***At equal thickness:***
  - ⇒ ***GXW1 FRC offers lower cost and weight than balsa***
  - ⇒ ***GXW1 FRC heavier (3.4 kg/m^2) than PVC foam, slightly less expensive***
- ***FRC may enable thickness reduction compared to PVC foam - not yet accounted for***

Weight and Cost–
75mm Shear Web Cores

- **GXW1 not optimized versus PVC foam. Consider "GX Light" designed as PVC foam replacement for shear web**





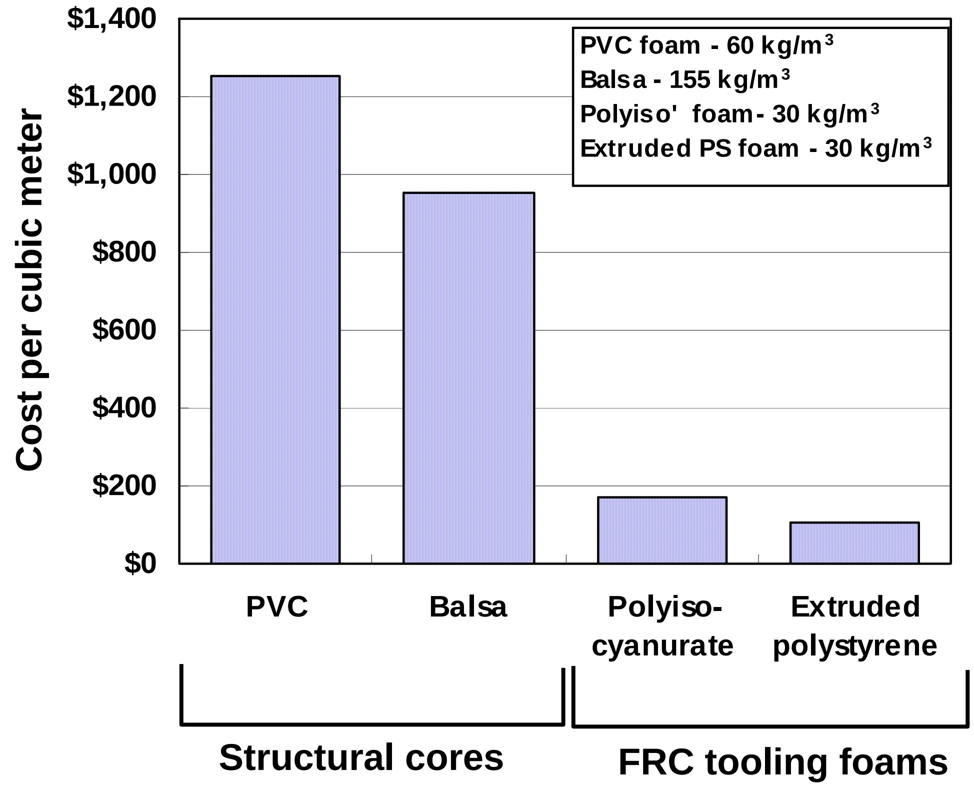
- **At equal thickness:**
  - ***⇒ "GX Light" FRC 26% less expensive than PVC foam***
  - ***⇒ "GX Light" FRC only slightly heavier (1.4 kg/m^2) than PVC foam***
- ***FRC may enable thickness reduction compared to PVC foam - not yet accounted for***

FRC Cost Basis

How can FRC compete?

- **Low cost input materials**
  - Low-property foam serves only as tooling material
  - E-glass roving used in winding
- **Low-cost processes**
  - Gang saw
  - High-speed winder
  - Foam laminator

Characteristic Costs of Foams and Balsa



Conclusions and Comments

- **TYCOR® Fiber-Reinforced Core (FRC) is a tailorable orthotropic core. Processes well for infusion-molded blades**
- **Compared to balsa: GX FRC provides equivalent buckling resistance to balsa at approximately the same thickness, and provides cost and weight savings.**
- **Compared to PVC foam:**
  - **GX FRC provides equivalent buckling resistance to PVC foam at <u>reduced thickness.</u> Further studies planned to better quantify.**
  - **GX provides cost savings.**
  - **GX provides weight savings compared to PVC contour core, slightly heaver for equal-thickness rigid core.**
- **Long-term benefit of FRC: <u>Availability</u>**
  - **Commodity input materials (insulation foam, E-glass roving)**
  - **Low capital investment for new production lines**

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